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Abstract

A large, civilian, multiengine transport MD-11 airplane control system was recently modified to perform as an emergency backup controller using engine thrust only. The emergency backup system, referred to as the propulsion-controlled aircraft (PCA) system, would be used if a major primary flight control system fails. To allow for longitudinal and lateral–directional control, the PCA system requires at least two engines, and is implemented through software modifications. A flight-test program was conducted to evaluate the PCA system high-altitude flying characteristics and to demonstrate its capacity to perform safe landings. The cruise flight conditions, several low approaches, and one landing without any aerodynamic flight control surface movement were demonstrated. This paper presents results that show satisfactory performance of the PCA system in the longitudinal axis. Test results indicate that the lateral–directional axis of the system performed well at high altitude but was sluggish and prone to thermal upsets during landing approaches. Flight-test experiences and test techniques are also discussed with emphasis on the lateral–directional axis because of the difficulties encountered in flight test.

Nomenclature

$C_{l\beta}$	roll caused by the dihedral term
c.g.	center of gravity
EPR	engine pressure ratio
FADEC	full-authority digital engine control computers
FCC	flight control computer
H	altitude, ft
K_{lat}	lateral feed-forward gain, lb/deg
K_{lc}	heading error feed-forward gain, deg
K_{lead}	command prefilter gain
K_{phid}	bank angle rate feedback gain, deg/sec
K_{pr}	turn coordination feedback gain, deg/sec
KCAS	knots calibrated airspeed
LSAS	longitudinal stability augmentation system
$m.a.c.$	mean aerodynamic chord, percent
p	roll rate, deg/sec
PCA	propulsion-controlled aircraft
PCALAT	lateral PCA engine command, lb
q	pitch rate, deg/sec
r	yaw rate, deg/sec
s	LaPlace transform
t	time, sec
uu	perturbed forward velocity (x axis), ft/sec

V	airspeed, kn
v_{err}	velocity error
vv	perturbed side velocity (y axis), ft/sec
W	takeoff gross weight, lb
ww	perturbed downward velocity (z axis), ft/sec
α	angle of attack, deg
γ	flight-path angle, deg
γ_{cmd}	flight-path angle command, deg
γ_{err}	flight-path angle error, deg
ζ	damping ratio
θ	pitch attitude angle, deg
$\dot{\theta}$	pitch attitude angle rate, deg/sec
λ	eigenvalues
λ_{cl}	closed-loop PCA eigenvalues
λ_{ol}	longitudinal open-loop eigenvalues
Φ	bank angle, deg
Φ_{cmd}	bank angle command, deg
ϕ	roll attitude, deg
$\dot{\phi}$	bank angle rate, deg/sec
Ψ	heading angle, deg
Ψ_{cmd}	heading angle command, deg
Ψ_{step}	heading step
ω	frequency, rad/sec

Introduction

Aircraft flight control systems are designed with extensive redundancy to ensure a low probability of failure. However during recent years, several aircraft have experienced major flight control system failures, leaving engine thrust as the only usable control effector. In some of these emergency situations, the engines were used "open-loop" to maintain control of the flightpath and bank angle of the airplane. Perhaps, the best known use of manual throttles-only control occurred in July 1989 on United Airlines flight 232. At cruise conditions, a DC-10 (McDonnell Douglas Aerospace (MDA), Long Beach, California) suffered an uncontained tail engine failure that caused the loss of all hydraulics. After the failure, the airplane trimmed at approximately 210 kn with a significant yaw angle because of damage to the center engine nacelle. Under extremely difficult circumstances, the crew used wing engine throttles for control and was able to crash land at the Sioux City, Iowa, airport, and over one-half of the people onboard were saved.[1] In the majority of cases surveyed, major flight control system failures have resulted in crashes with a total of over 1200 fatalities.[2]

The challenge was to create a sufficient degree of control through thrust modulation to control and safely land an airplane with severely damaged or inoperative control surfaces. The objective of the propulsion-controlled aircraft (PCA) emergency backup system is to command the engines to maneuver the airplane to a safe landing without moving the normal aerodynamic control surfaces. This system requires that the airplane have at least two engines, preferably two wing engines, functioning. In addition, it is assumed that the normal control surfaces are not locked in a hardover position where aerodynamic forces would exceed the moments resulting from the engines thrust.

To investigate the PCA concept, the NASA Dryden Flight Research Center, Edwards, California, performed nonlinear and linear analytical studies and conducted several flight-test programs. Gross control can be obtained by using the throttles in the open-loop sense (manual throttles-only), but making a safe runway landing is exceedingly difficult because of low phugoid and dutch roll damping coupled with the high pilot work load near the ground.[2–6] To improve performance and reduce the pilot work load, the PCA program was developed.

This paper concentrates on the difficulties encountered during flight test of the lateral–directional controller and the solutions found. Comparisons of linear simulation models to flight-test results and control law design processes are presented. In addition, an overview of the longitudinal controller is presented.

Test Vehicle Description

Figure 1 shows the MD-11 airplane, a large, long-range, three-engine, wide-body transport. This airplane is 202 ft long, has a wing span of 170 ft, and a maximum takeoff gross weight (W) of 618,000 lb.

Flight Control Systems

The MD-11 airplane has a mechanical control system with stability augmentation provided by the flight control computers (FCC) and with irreversible hydraulically powered actuators. Three independent systems provide hydraulic power for intended fail-safe capability. Essential control functions can be maintained by any one of the three systems. Dual elevators on each

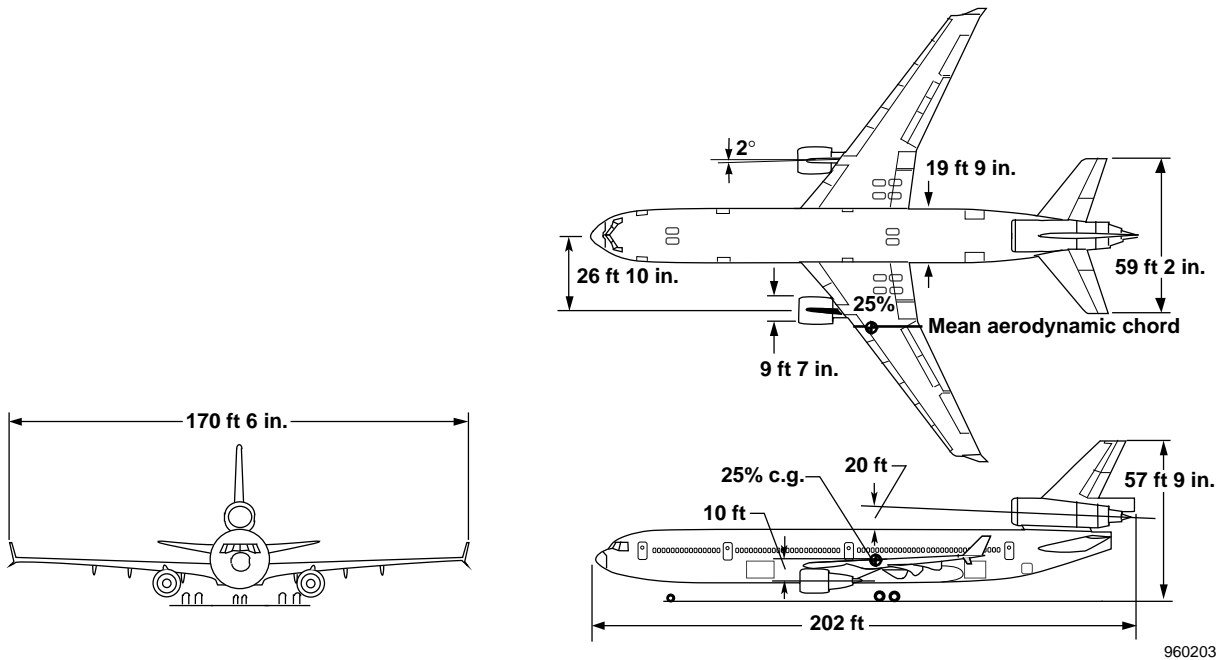American Institute of Aeronautics and Astronautics

Figure 1. The MD-11 airplane.

horizontal stabilizer provide pitch control, and pitch trim is provided by a moveable horizontal stabilizer. Roll control is provided by inboard and outboard ailerons supplemented by wing spoilers. Yaw control is provided by a dual rudder mounted on a single vertical stabilizer.

The basic control design for the lateral dynamics is called the yaw damper and longitudinal stability augmentation system (LSAS) for the pitch dynamics. Hydraulic devices provide the force through control cables from the control column that moves the aerodynamic surfaces commanded from FCC. The FCC were built by Honeywell, Inc., Phoenix, Arizona, and operate at 20 samples/sec.

The MD-11 airplane is equipped with a flight management system which integrates autopilot, navigation, and autoland functions. The autopilot control includes a thumbwheel for commanding flightpath angle, γ_{cmd}, and a heading knob for commanding the desired heading, Ψ_{cmd} .

Engines

Three Pratt & Whitney (Palm Beach, Florida) PW4460 high-bypass ratio turbofan engines in the 60,000-lb thrust class power the MD-11 airplane. Two engines are mounted in underwing pods. The third engine is located at the base of the vertical stabilizer. Each engine has a full-authority digital engine control (FADEC) system in which the software was modified for the PCA program. The modification allows for an increased range of engine pressure ratio (EPR) commands to be sent from the FCC. The range was increased from 5 percent of the trimmed EPR to approximately 0.9 to 1.50 percent. The wing engines are 121 in. below the nominal vertical center of gravity (c.g.), and the tail engine is 240 in. above the vertical c.g. with its thrust axis inclined 2.5° (nozzle pointing down). The crew controls the engines with electronic throttles which command a power setting based on EPR.

As is typical for high-bypass turbofan engines, thrust response at low power settings is initially slow. Once thrust levels exceed 20 percent, the engine response improves dramatically. An "approach idle" setting when the flaps are extended beyond 27°, maintains the idle revolutions per minute at a sufficiently high level so that the 8 sec from idle to full power requirement can be met. A cruise idle or minimum idle setting can require as much as 12 sec to go from idle to full power.[2] If PCA were engaged with minimum idle setting, a pilot-induced oscillation could occur because of the large time lags; therefore, another modification to the FADEC system included setting the approach idle when the PCA system was engaged.

PCA Control System Design

The design of the longitudinal and lateral–directional control laws assumes that the normal control surfaces are not functioning and are not in a hardover position. Given the limited engine bandwidth, PCA control requires a relatively stable open-loop plant or slightly unstable poles. As a transport airplane, the MD-11 easily meets this criterion. Of the cases investigated, the least unstable open-loop lateral–directional poles were for a flight condition of 195 kn/0.0° flaps with eigenvalues (λ) located at 0.021, –0.051 + 0.764j, –0.051 – 0.764j, –0.529. The dutch roll mode (–0.051 ± 0.764j) has a damping ratio (ζ) of 0.067. In addition, the lease stable open-loop longitudinal eigenvalues were for a flight condition of 145 kn/28° flaps with the eigenvalues located at 0.004 + 0.152j, 0.004 – 0.152j, –0.433 + 0.468j, and –0.433 – 0.468j. The phugoid mode was slightly unstable with a damping ratio of –0.024 and a time-to-double amplitude of 1847.0 sec. The MD-11 engine bandwidth is limited to approximately 2 rad/sec. The PCA system uses engine thrust modulation driven by a closed-loop controller to increase the damping and allow the pilot to land safely. In the longitudinal axis, the phugoid mode needed improvements. In the lateral–directional axis, the dutch roll poles needed enhancement.

The initial PCA system was designed to have minimal impact on existing hardware and software. The resulting system only required software changes. The flight control panel was used for the pilot input paths. The heading control knob was used for the lateral–directional controller, and the flightpath angle thumbwheel was used for the longitudinal axis. Collective thrust commands to the wing engines provided pitch or longitudinal control, and differential thrust commands provided lateral–directional control.

The PCA system was designed with the flexibility to change the control gains in flight (within safety limits), allowing for improved performance or robustness. However for safety reasons, the controller architecture could not be modified other than zeroing out selected feedback paths.

Nonlinear simulators were heavily used to adjust the initial gains determined from classical linear design. These control laws were developed by a team from McDonnell Douglas Aerospace, Honeywell, Inc., Pratt & Whitney, and NASA.

Longitudinal Control

The longitudinal control law commands the flightpath angle and augments phugoid damping (fig. 2). The feedback signals selected were pitch attitude, θ; pitch attitude rate, $\dot{\theta}$; velocity error, v_{err} and flightpath angle. Velocity feedback was not used initially, but it was added later for improved longitudinal control. These signals were already available to the primary stability
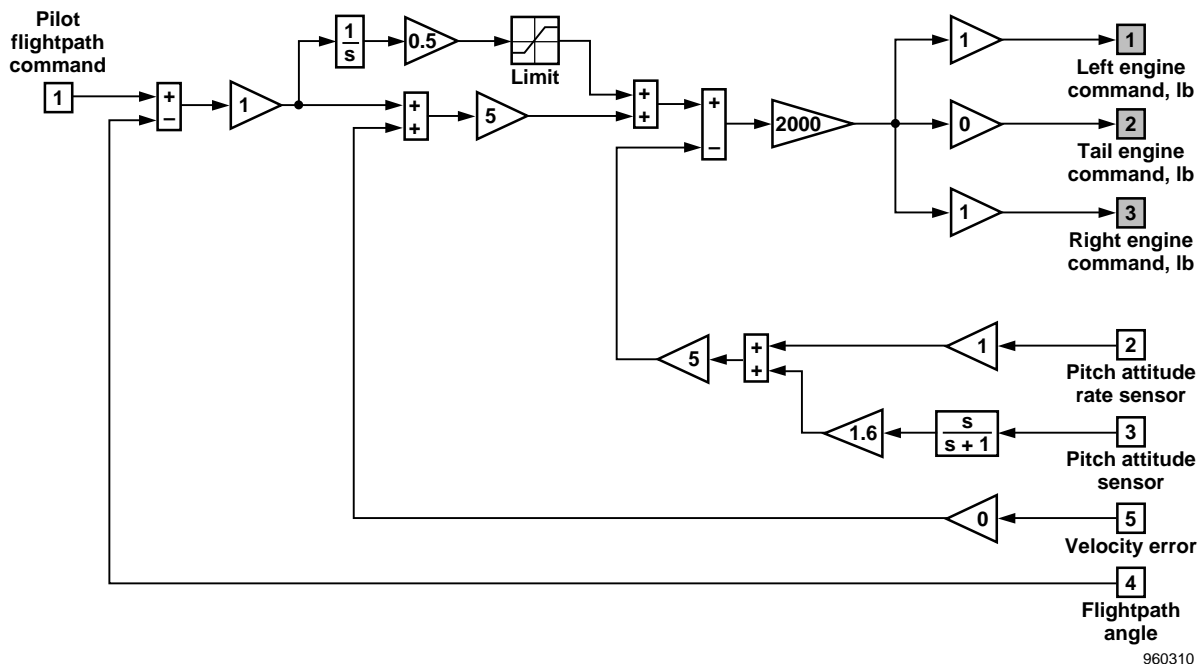

Figure 2. Longitudinal MD-11 PCA control law.

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augmentation system. Flightpath angle error, γ_{err}, is passed through a proportional plus limited integral compensator to maintain an acceptable tracking task for the pilots. Washed out pitch attitude and attitude rate are summed after the integrator for improved phugoid damping. Reference 7 gives detailed information regarding the longitudinal controller.

Lateral–Directional Control

Lateral–directional control is obtained by using differential throttle inputs to generate yaw, resulting in roll caused by the dihedral term, $C_{l\beta}$. The lateral–directional control law tracks heading angle commands, Ψ_{cmd} (fig. 3). The feedback signals selected to improve the dutch roll damping and closed-loop performance consist of bank angle, Φ; bank angle rate, $\dot{\phi}$; yaw rate, r; and heading angle, Ψ. Bank angle rate was included for dutch roll damping, and yaw rate and bank angle were included for turn coordination. The resulting output from the PCA lateral–directional controller (PCALAT) is then used to modulate the thrust of each engine.

Linear Analysis

In the longitudinal and lateral–directional axes, classical methods were initially used to design the controllers. The classical single–input–single–output methods included root locus and frequency analysis methods, such as Bode or Nyquist techniques. Classical linear design was used for acceptable rise time and damping characteristics. This design was also evaluated in a nonlinear simulation where the gains were adjusted to increase damping or performance.

From linear analysis, the longitudinal open-loop eigenvalues, λ_{ol}, and the closed-loop PCA eigenvalues, λ_{cl}, are shown in table 1 as a representative case, along with the damping ratio. Flight conditions were H = 12,000 ft, V = 175 kn, flaps = 28°, slats = extend, c.g. = 23 percent *m.a.c.*, W = 360,000 lb, and gear down. The phugoid damping increased from barely stable (0.056) to highly damped (0.657) when the PCA system closed the loop. The stability margins for flightpath loop are gain margin = 13 dB @ ω = 1.02 rad/sec and phase margin = 47° @ ω = 0.28 rad/sec. These margins are acceptable for the stability criteria of 6 dB and 45°. The appendix contains the plant model.

From linear analysis, table 2 lists the lateral–directional open-loop eigenvalues, closed-loop PCA eigenvalues, and damping ratios. Flight conditions were H = 12,000 ft, V = 175 kn, flaps = 28°, slats = extend, c.g. = 23 percent *m.a.c.*, W = 360,000 lb, gear down and default gains. The dutch roll damping increased from 0.117 to 0.61 with the closed-loop
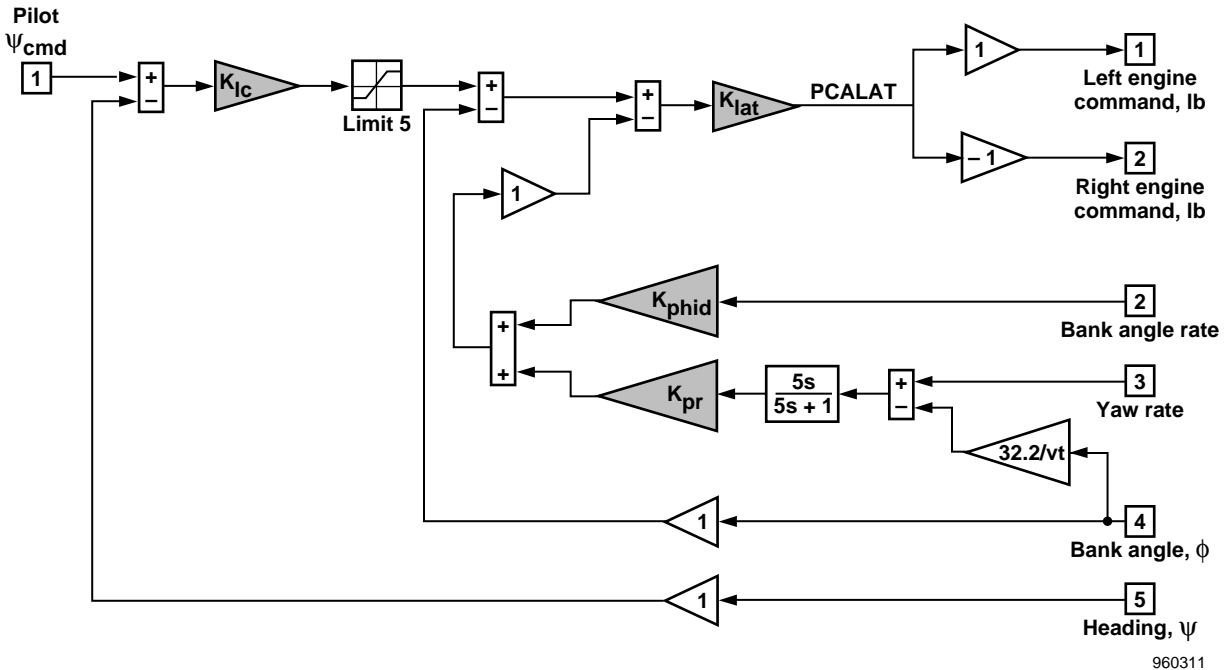
Figure 3. Lateral–directional control law. Note that shaded boxes $(K_{lc}, K_{lat}, K_{pr}, K_{phid})$ were modified gains during flight test.

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Table 1. The MD-11 airplane longitudinal open-loop and PCA closed-loop eigenvalues.

	Open loop		Closed loop	
	Eigenvalue	Damping ratio	Eigenvalue	Damping ratio
Phugoid	$-0.006 \pm 0.109j$	0.056	$-0.168 \pm 0.193j$	0.657
Short period	$-0.410 \pm 0.602j$	0.563	$-0.440 \pm 1.13j$	0.368
Engine	-2.00	1.0	-2.15	1.0
Control and integrator	---	---	-0.069	1.0
Control and washout	---	---	-0.375	1.0

Table 2. The MD-11 lateral–directional open-loop and PCA closed-loop eigenvalues.

	Open loop		Default closed loop	
	Eigenvalue	Damping ratio	Eigenvalue	Damping ratio
Dutch roll	$-0.082 \pm 0.692j$	0.117	$-0.291 \pm 0.379j$	0.61
Spiral mode	0.026	-1.0	$-0.134 + 0.085j$	0.85
Rolling mode	-0.801	1.0	$-0.134 - 0.085j$	0.85
Engine	-2.00	1.0	$-0.970 \pm 1.15j$	0.64
Control and washout	---	---	-0.350	1.0

system allowing for good airplane response characteristics. In addition, the stability margins for the heading angle loop are gain margin = 26 dB @ ω = 1.47 rad/sec and phase margin = 69° @ ω = 0.43 rad/sec. The closed-loop analysis is for the default gains used in the initial flight test phase; however, the sluggish response of the airplane required a different set of gains to improve the roll rate. The appendix presents the plant model.

Simulation

Flight control system design and analysis for aircraft rely on mathematical models of the vehicle dynamics. These models are brought together to form a linear or nonlinear simulation for design and evaluation. The development of the PCA control algorithms used a six-degree-of-freedom nonlinear simulation program and linearized state-space models. In addition, a fixed-base,

piloted, flight deck simulator was used. This simulator had an option to run hardware-in-the-loop which included FCC and FADEC.

For linear analysis and simulation, the engines were modeled as a first-order LaPlace transform shown in equation 1, with a rate limit of one-half the engine thrust output in pounds per second (eq. 2).

$$eng(s) = \frac{1}{(0.5s + 1)} \qquad (1)$$

$$Eng_{rate} = trim_{thrust/2} \text{ (lb/sec)} \qquad (2)$$

Evaluation of this simple model is shown in the Results and Discussion section through time history matching of flight and simulation aircraft angular position and rates.

Software Implementation

The FCC provides a host of functions including autopilot, autothrottle, and navigation. These computers also provide a flight management system. The PCA logic interfaced with existing sensor signals and sent commands to the engine FADEC computers over a 429 data bus. Pratt & Whitney modified the engine controllers to accept a full-authority EPR command from the FCC which ranged from 0.9 to approximately 1.5. The PCA system incorporated a safety disengage capability which was accomplished by the pilot through moving the throttle lever or by pressing a cockpit FCC switch. These features provided pilots with normal throttle and conventional control surface response if needed.

Flight Test Maneuvers

A series of evaluation maneuvers were flown at a condition of 12,000 ft, 175 KCAS, gear down, flaps extended to 28°, slats extended, c.g. at 23 percent *m.a.c.* and 360,000 lb. The pilot stabilized the airplane at this flight condition with the PCA system turned on and completed a series of step inputs. During PCA flight-test operations, the hydraulic system was powered with the control surfaces fixed.

To increase confidence in the system, low approaches were performed in a graduated series of decreasing altitudes until a landing was accomplished. Note that the flaps were set at 28° (takeoff flap position) to obtain low landing speeds. Other flight conditions were flown, such as 0.0° flaps and a range of c.g. positions (23 to 31 percent *m.a.c.*), altitudes, and speeds.[2] Low approaches to 50 ft above ground were flown with 0.0° flaps, gear down, and an airspeed of approximately 195 kn. These cases were not allowed to touch down because of programmatic decisions and airplane rental agreements. Although the 0.0° flap approach speeds would have been pushing the upper limitations of a normal MD-11 landing (204-kn tire speed), during an emergency these conditions would be acceptable. The PCA flying qualities with the flaps at 0.0° were well-behaved. No noticeable stability or performance degradation occurred.

Results and Discussion

This section describes the linear simulation to flight result comparison for the longitudinal and lateral–directional axes. In addition, results are presented for the improved lateral–directional controller and one MD-11 PCA landing.

## Comparison of Simulation to Flight Evaluation

Figure 4 shows a longitudinal axis comparison of flight and linear simulator results for a series of flightpath angle step inputs at a flight condition of 175 kn, 12,000 ft, 28° flaps, and gear down. There is an overshoot of the flightpath response compared to command of approximately 30 percent for both the simulator and flight-test results. This overshoot did not concern the pilots even at low altitudes. In general, the linear model represents the flight dynamics reasonably well and is adequate for control design. Reference 7 provides additional information regarding the different longitudinal modes flown.

Figure 5 shows a lateral–directional axis comparison of flight and linear simulation results for a heading angle command, step input using the default gains at the previous flight condition. The time history traces of the simulator model matched the flight data reasonably well. However, the pilots rated the lateral–directional response poor near the ground, and modifications to improve the sluggish response were needed.

The piloted simulations did indicate some lateral–directional challenges but not to the extent of the flight test evaluations. Matching a pilot's work load, or gain, in a simulator to flight is a difficult task, especially during a turbulent day with a low bandwidth control system. The level of turbulence has a large impact on the PCA controller performance and pilot ratings, especially in the roll axis. These approaches and landing occurred on a hot August day with light turbulence. Although the winds were light (approximately 9-kn head wind), high thermal disturbances caused roll upsets.
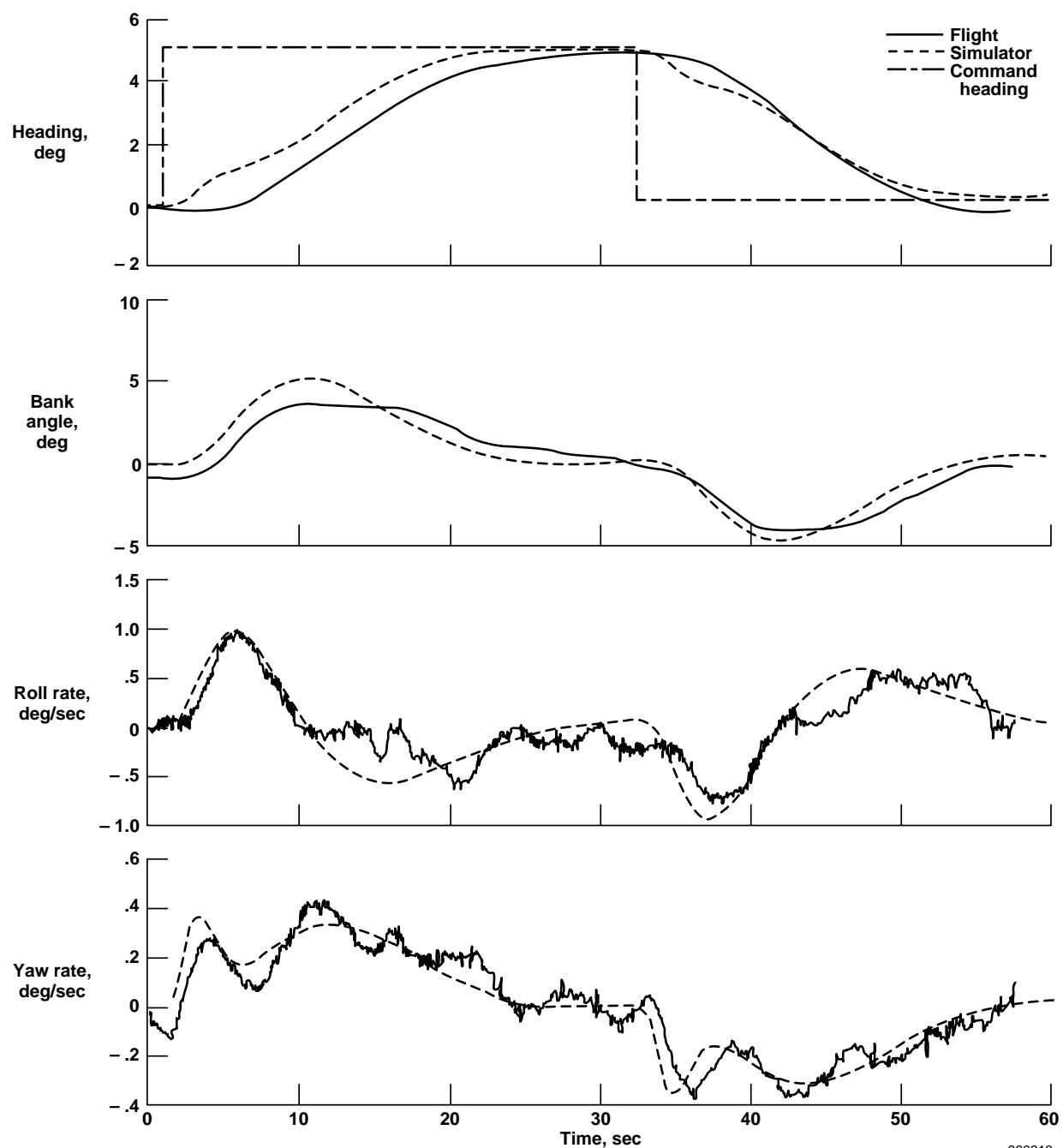
Lateral–Directional Axis Modification

The major controls challenge of the MD-11 PCA system was to improve the lateral–directional axis response without a new control law release. The pilots rated the response marginal at best. Lateral–directional control gains were modified to improve the performance. The heading error feed forward, lateral feed forward, turn coordination feedback and bank angle feed back (K_{lc}, K_{phid}, K_{lat}, and K_{pr}) gains were selected for modification (fig. 3). The K_{phid} and K_{pr} gains were used as damping adjustment parameters, while the K_{lc} and K_{lat} gains affected the initial response. Six gain sets were flight tested, but only two are presented here: the default set and T6 gain set. Gain set T6 gave the largest roll rates per degree of commanded input and was the gain set used for the PCA landing.

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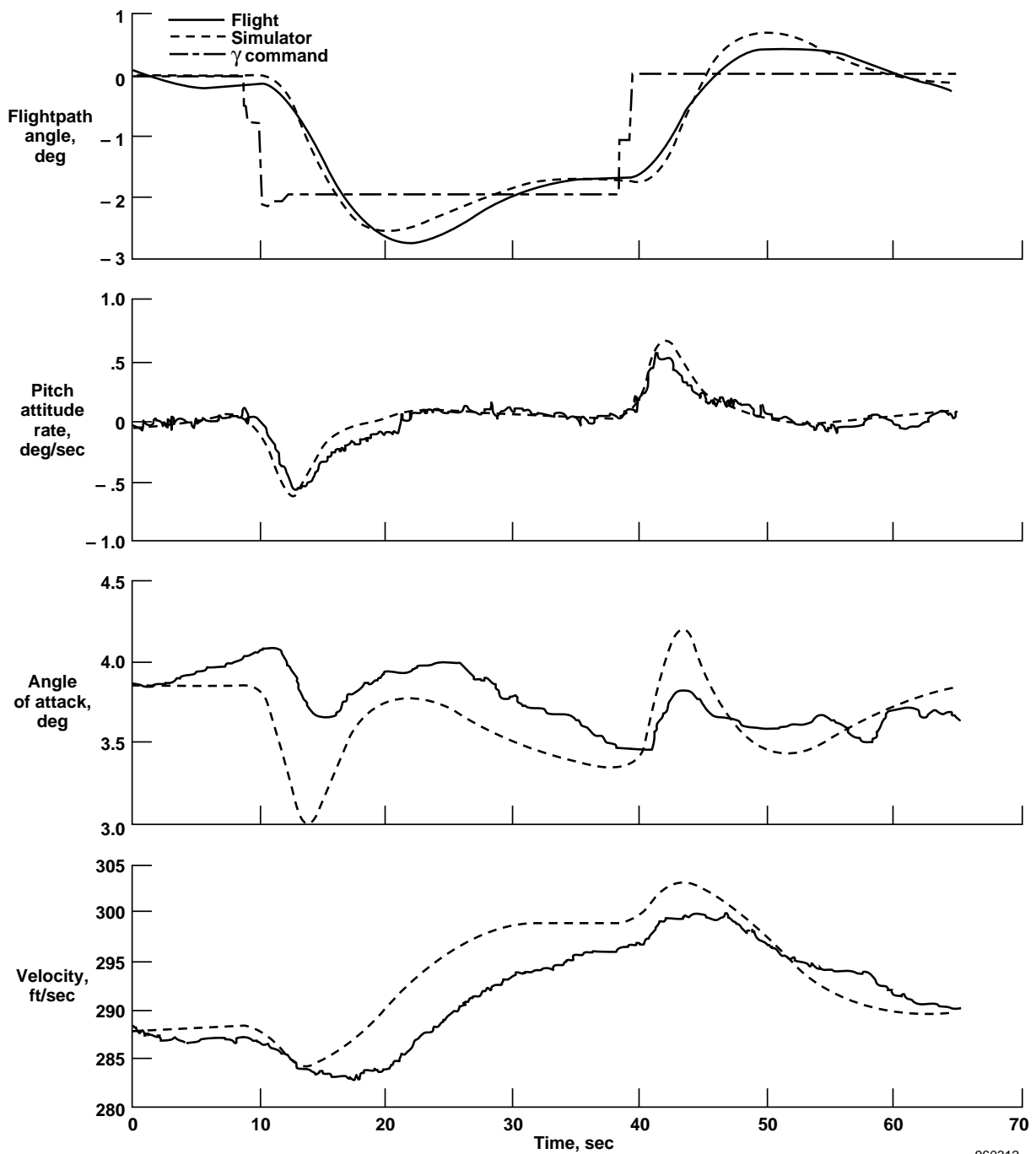
Figure 4. Comparison of flight and linear simulation flightpath angle step response.

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Figure 5. Comparison of flight and linear simulation heading step response using the default gain set.

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Using linear root locus analysis and relying on nonlinear simulation runs, the gains were modified (table 3). The control system with these gains was then tested in flight by in-putting the variables using the Multifunction Control and Display Unit. Table 4 lists the closed-loop eigenvalues of the default gain set and the T6 gain set. Flight conditions were H = 12,000 ft, V = 175 kn, flaps = 28°, slats = extend, c.g. = 23 percent *m.a.c.*, W = 360,000 lb, gear down, and default gains.

Table 3. Lateral–directional modified control gains for improved roll response.

	K_{lc}	K_{lat}	K_{pr}	K_{phid}
Default	1.0	1000.0	10.0	1.5
T6 gains	1.5	1500.0	6.7	1.0

Figure 6 shows the flight comparison between the default gains and T6 gains at a flight condition of 175 kn, 12,000 ft, 28° flaps, and gear down. A heading change of 5° was commanded, and the time to reach 90 percent of the final value (rise-time) was calculated. The rise time for the default gain set was 19.5 sec, and the T6 gain set was 12 sec. The heading performance was improved by 38 percent using the T6 gain set. The maximum body axis roll rate, p, in figure 6 increased 77 percent using T6 gains but at the cost of reduced dutch roll damping. Note the roll and yaw rate traces. (See also table 4.)

Figure 6 also shows the EPR of the left and right engines for both gain sets. The T6 gain set commanded more engine activity than the default gains. The pilot's comments on the T6 gain set response were much more favorable than those regarding the default gain response.

The comments made were; "I could feel the response 'kick-in' faster with T6 compared to the default set;" and "I did not have to wait as long for the airplane to 'catch-up' to my input command." The T6 gain set was used for the PCA landing.

One control law change that should improve the heading response without decreasing the dutch roll damping would be to apply a lead–lag compensator in the pilot's forward path (fig. 7) while using the default gain set. This method would have the same closed-loop poles as the default gain set, with increased lead to the input signal. Unfortunately, there was no way to add a lead–lag filter on the input signal without a new control law release. The next phase of flight test will include an equivalent lead–lag filter. One possible drawback would be engine saturation, and further testing is needed in this area.

Landing Phase

After the lateral–directional axis response was improved, and without any longitudinal axis changes, a successful landing was performed using the PCA control system. In a trimmed 28° flaps condition, a landing was performed without any control surface movement, simulating a total hydraulics pressure loss. The results are shown in figure 8, with the landing occurring at time = 83 sec. During the approach, a large thermal upset caused the airplane to bank over to an angle of approximately 8° just after a lateral command change (time = 60 sec). The lateral–directional axis controller commanded a restoring signal to remove the error, without pilot inputs. The 7° upset at time = 12 sec was caused by the pilot's commanded input as shown in the heading trace (time = 5 sec). Angle of attack, α, decreased just before landing because of ground effects. The gust rejection characteristics are less than desirable;
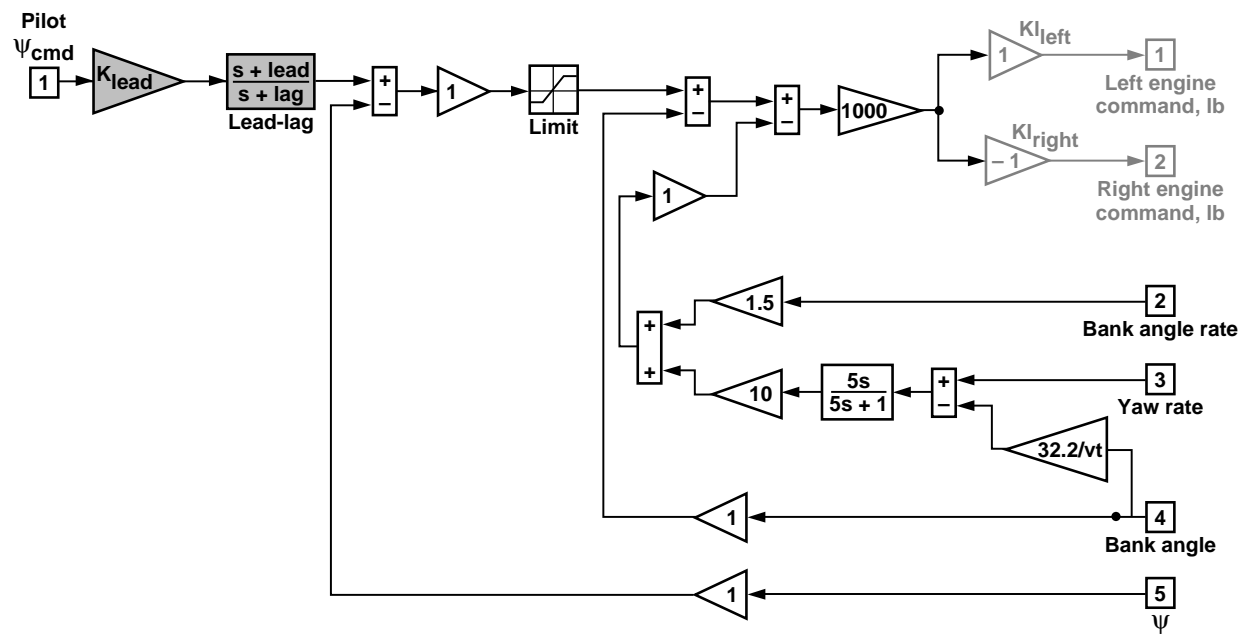
Table 4. The MD-11 lateral–directional PCA default and T6 gain set closed-loop eigenvalues.

	Default closed loop		T6 gain set	
	Eigenvalue	Damping ratio	Eigenvalue	Damping ratio
Dutch roll	–0.291 ± 0.379j	0.610	–0.236 ± 0.419j	0.409
Spiral mode	–0.134 + 0.085j	0.85	–0.204 + 0.081j	0.93
Rolling mode	–0.134 – 0.085j	0.85	–0.204 – 0.081j	0.93
Engine	–0.970 ± 1.15j	0.64	–0.904 ± 1.100j	0.63
Control and washout	–0.350	1.0	–0.450	1.0

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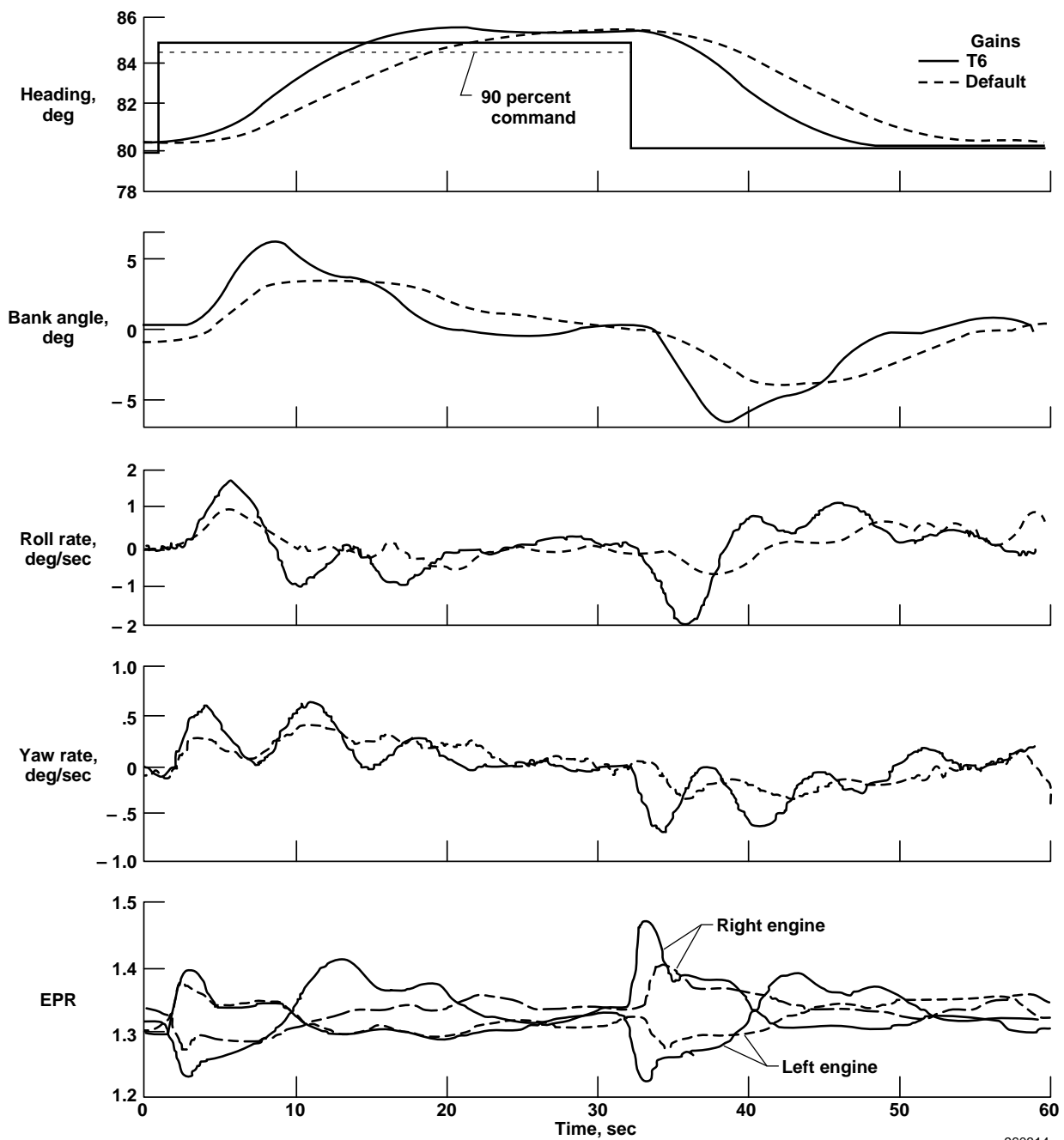
Figure 6. The flight heading step response using the default and T6 gains.

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Figure 7. Lateral–directional control law B.D. phase 2 lead–lag controller.

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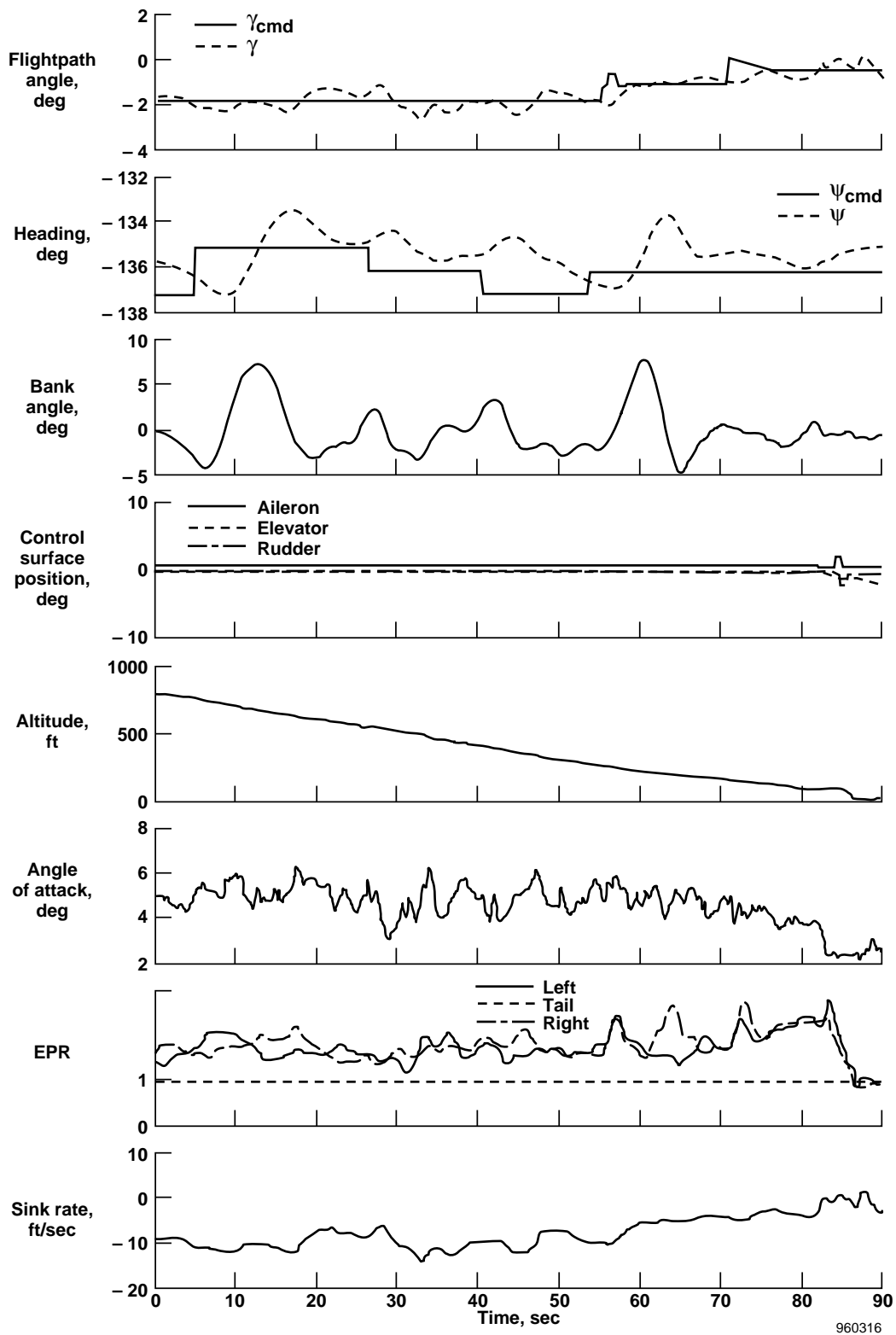
Figure 8. Pilot-commanded landing with 28° flaps and an airspeed of 175 kn.

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note the bank angle trace. The design criteria was to have the bank angle error less than ±5° during the approach and landing task. Incorporation of a lead–lag filter with the reduced default gains should help with the gust sensitivity problem by providing increased lead response without reducing the dutch roll damping.

Concluding Remarks

An emergency backup control system using engine thrust only was designed and flight tested on a large, civil transport MD-11 airplane. This report describes the longitudinal and lateral–directional propulsion controlled aircraft (PCA) control system, and compares simulation and flight-test results. Flight data comparisons with linear models were shown with the emphasis on the lateral–directional sluggish response. The control system was designed from the onset with the flexibility to change several control gains in flight.

The longitudinal control system performed well during the high-altitude operations, low approaches, and landing. The pilots rated the longitudinal characteristics good, with minor pilot compensation needed. The performance was satisfactory; therefore, changes were not required during the first phase of flight test.

The flaps were set at 28° (takeoff flap position) to obtain low landing speeds. Other flight conditions were flow, such as 0.0° flaps and a range of center-of-gravity (c.g.) positions (23- to 31-percent *m.a.c.*), altitudes, and speeds. Low approaches to 50 ft above ground level were flown with 0.0° flaps, gear down, and an airspeed of 195 kn. These cases were not allowed to touch down. Although the 0.0° flap approach speeds would have been pushing the upper limitations of a "normal" MD-11 landing (204-kn tire speed), during an actual emergency, the conditions would be acceptable. The PCA flying qualities with the flaps at 0.0° were well-behaved.

The original lateral–directional response was considered too sluggish near the ground because of wind gusts. Control law changes used to improved the response were shown and compared to the initial system. The roll response increased approximately 77 percent with a new gain set (T6), but the dutch roll damping decreased. Future work may include a lead–lag filter with the default gains for improved response. The default gain set has greater dutch roll damping and will inherently improve gust rejection. Allowing for gain changes in flight improved lateral–directional response

without the need for time consuming and expensive control law updates.

This backup control system could be used in the event of the airplane suffering a major primary flight control system failure, such as a total hydraulic pressure loss. The PCA system has limited control power which may not be sufficient to handle surface hardovers or large mistrim configurations. However in the absence of large mistrim configurations, the PCA system provides a method for returning the airplane to the airport and landing without the aid of aerodynamic control surfaces. The PCA system changes a flight situation where there is an extremely high work load (using manual throttle inputs) to a viable piloting task.

APPENDIX

MD-11 PCA PLANT MODEL
(H = 12,000 ft, V = 175 kn)

State Equation Model Form

$$\dot{x}(t) = Ax(t) + Bu(t) \quad \text{where} \quad A = A_{lon} \text{ or } A_{lat}$$

$$y = Cx(t)$$

$$x_{lon} = [uu\ ww\ q\ \theta]^T$$

$$x_{lat} = [vv\ r\ p\ \phi]^T$$

$$u = [\delta_{left\ eng}\ \delta_{tail\ eng}\ \delta_{right\ eng}]^T$$

Longitudinal Dynamics

$$A_{lon} = \begin{bmatrix} -2.115e-2 & 9.172e-2 & -3.753e-1 & -5.605e-1 \\ -1.347e-1 & -5.656e-1 & 5.927 & -3.333e-2 \\ 4.679e-3 & -6.454e-2 & -2.458e-1 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$B_{lon} = \begin{bmatrix} 9.153e-5 & 9.152e-5 & 9.133e-5 \\ 4.427e-6 & 1.371e-6 & -1.542e-6 \\ 2.962e-5 & -3.600e-5 & 1.895e-5 \\ 0 & 0 & 0 \end{bmatrix}$$

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Lateral–Directional Dynamics

$$A_{lat} = \begin{bmatrix} -1.219e-1 & -5.800 & 3.341e-1 & 5.605e-1 \\ 4.941e-2 & 1.373e-1 & -6.361e-2 & 4.025e-5 \\ -1.80e-1 & 8.104e-1 & -6.797e-1 & -2.914e-5 \\ 0 & 5.946e-2 & 1 & 0 \end{bmatrix}$$

$$B_{lat} = \begin{bmatrix} 2.748e-6 & -3.678e-9 & -2.745e-6 \\ 5.429e-5 & 5.009e-9 & -5.429e-5 \\ 7.164e-6 & -3.626e-9 & -7.256e-6 \\ 0 & 0 & 0 \end{bmatrix}$$

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A large, civilian, multiengine transport MD-11 airplane control system was recently modified to perform as an emergency backup controller using engine thrust only. The emergency backup system, referred to as the propulsion-controlled aircraft (PCA) system, would be used if a major primary flight control system fails. To allow for longitudinal and lateral–directional control, the PCA system requires at least two engines and is implemented through software modifications. A flight-test program was conducted to evaluate the PCA system high-altitude flying characteristics and to demonstrate its capacity to perform safe landings. The cruise flight conditions, several low approaches and one landing without any aerodynamic flight control surface movement, were demonstrated. This paper presents results that show satisfactory performance of the PCA system in the longitudinal axis. Test results indicate that the lateral–directional axis of the system performed well at high altitude but was sluggish and prone to thermal upsets during landing approaches. Flight-test experiences and test techniques are also discussed with emphasis on the lateral–directional axis because of the difficulties encountered in flight test.

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